

NASA STATISTICAL ENGINEERING SYMPOSIUM

A RELIABILITY-BASED TOOL FOR LIFE LIMIT EXTENSION OF THE SPACE SHUTTLE MAIN ENGINE (SSME) A SPACE SHUTTLE LESSON LEARNED

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Outline

- **Introduction**
- **The Need for the Tool**
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- **The Tool**
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- **The Application**
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Introduction – Related Material

- **“A Criterion for Establishing Life Limits”, 1990, by Gill Skopp and Al Porter.**
- **"A Statistical Approach for Risk Management of Space Shuttle Main Engine Components“, 1991 Probabilistic Safety Assessment and Management Conference, Beverly Hills, CA, by Fayssal M. Safie.**
- **“Lower Bound on Reliability for Weibull When Shape Parameter is not Estimated Accurately”, 1991, by Zhao Huang and Al Porter.**
- **“Weibull Analysis Handbook”, 1983, by R. Abernathy, C. Medlin, and G. Reinman.**

Introduction

- This work was done as part of the National Aeronautics and Space Administration (NASA) effort to introduce the use of Statistical/probabilistic models in managing the risk for critical Space Shuttle hardware.
- The result was a development of a statistically-based risk management tool to consistently and effectively extend the life limit of the Space Shuttle Main Engine (SSME) hardware based on the operational history combined with other engineering information.
- **The purpose of the tool was to provide a standardized approach to disposition structural life limitations.**
- The tool is called the Single Flight Reliability (SFR) criterion.

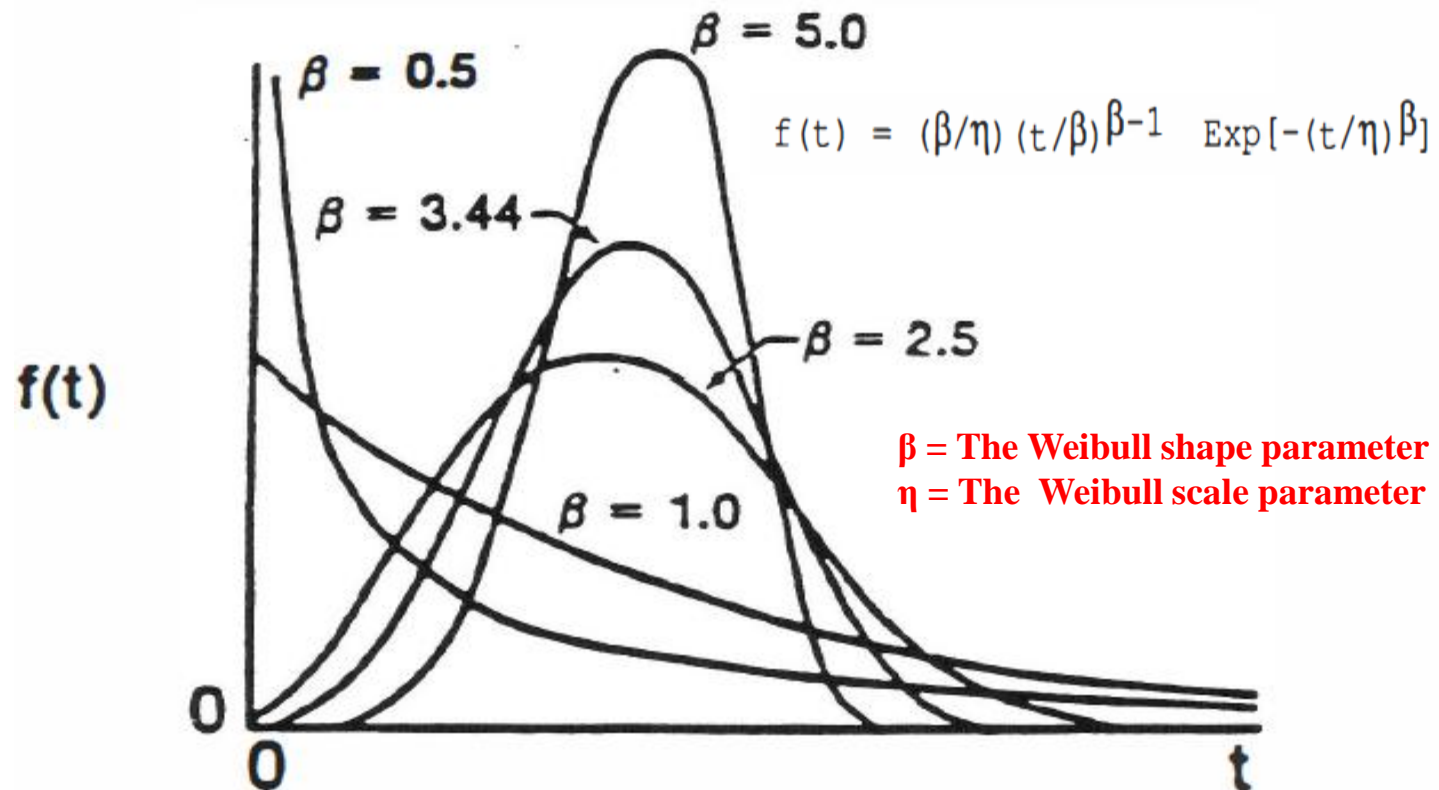
The Need for The Tool

The SSME Standard Flight Deviation Approval Request (DAR) Criteria

PARAMETER	I	II SFR	III	IV
DAR BASIS	ANALYSIS	OPERATING HISTORY	ANALYSIS	OPERATING HISTORY
MATERIAL PROPERTIES	PREDICTED MINIMUM /EXPECTED MINIMUM	UNIQUE CONDITIONS	EXPECTED MINIMUM	UNIQUE CONDITIONS
OPERATING STRESSES	PREDICTED LOADS MEASURED LOADS/ STRESSES EXTRAPOLATED LOADS/STRESSES	UNIQUE CONDITIONS	MEASURED LOADS/ STRESSES • CORRELATED TO 99/95	UNIQUE CONDITIONS
LIFE LIMITATIONS	BASED ON ANALYSIS	25% FLEET LEADER OR (2) → { STATIS. JUSTIFIED } ≤ 50% F/L 6 UNITS ≥ LIMIT	BASED ON ANALYSIS ≤ 50% F/L	≤ 50% FLT. LEADER/ FAILED UNIT 6 UNITS ≥ LIMIT
PERIODIC INSPECTION	NONE	NONE	25% F/L EXPOSURE	25% LIFE INTERVAL
LIFE FACTOR	HCF: 10, PRED. MIN. 4, EXP. MIN. LCF: 4 (2) →	4 { OR, 0.995/0.90 } { (RELIABILITY/ CONFIDENCE) }	HCF: 2 LCF: 4	2

The Mathematical Basis

The Weibull Probability Density Function



The Mathematical Basis

The Significance of the Weibull Shape Parameter

1. Infant mortality

- Inadequate burn-in, green run
- Misassembly
- Some quality problems

2. Random failures

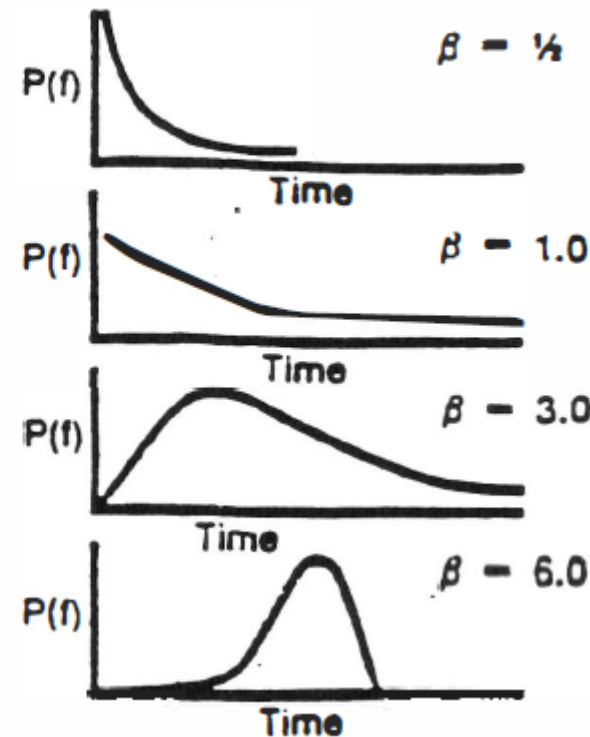
- Independent of time
- Maintenance errors
- Electronics
- Mixtures of problems

3. Early wearout

- Surprises
- Low cycle fatigue

4. Old age wearout (rapid)

- Bearings
- Corrosion



The Mathematical Bases – The Equations

The Weibull probability density function:

$$f(t) = (\beta/\eta) (t/\eta)^{\beta-1} \text{Exp}[-(t/\eta)^\beta] \quad (\text{two parameters})$$

The Weibull reliability and failure functions:

$$R(t) = \text{Exp}[-(t/\eta)^\beta] \quad (\text{two-parameters})$$

$$F(t) = 1 - \text{Exp}[-(t/\eta)^\beta]$$

β = The Weibull shape parameter

η = The Weibull scale parameter

t = The total time

m = the single mission time

$(1-\alpha)*100$ = The confidence level

The Weibayes

$$\eta \geq \left(\sum_{i=1}^n (t_i^\beta) / -\ln \alpha \right)^{1/\beta} \xrightarrow{\text{90\% Confidence}} \eta \geq \left(\sum_{i=1}^n (t_i^\beta) / 2.3 \right)^{1/\beta}$$

The Weibull conditional probability function:

$$P(T \geq t \mid T > t-m) = \text{Exp}[-(t/\eta)^\beta] / \text{Exp}[-((t-m)/\eta)^\beta]$$

The Tool - Assumptions

- **Infant mortality situations are excluded .**
- **For a specific SSME component, all units have the same basic configuration and geometry, and all are tested in the same environment.**
- **Only SSME components with extensive fleet hot fire experience with no failure history are considered.**

The Tool – The Process

- **The SFR Criterion uses a statistical approach to derive a life limit for a given component subject to a specified reliability and confidence level requirement.**
- **The statistical approach developed is based on Weibull time-to-failure distribution.**
- **Since the SFR Criterion applies only to components with no failures and the shape parameter of the Weibull distribution varies for different components, the Weibayes and a conditional Weibull reliability functions were used in combination with an optimization technique to derive a minimum life limit.**

The Tool - The Process (continued)

Calculating The Minimum Life:

- 1) Assume a value of (β) of approximately one.
- 2) For the operational history of the item under consideration, estimate (η) at the 90% confidence level using:

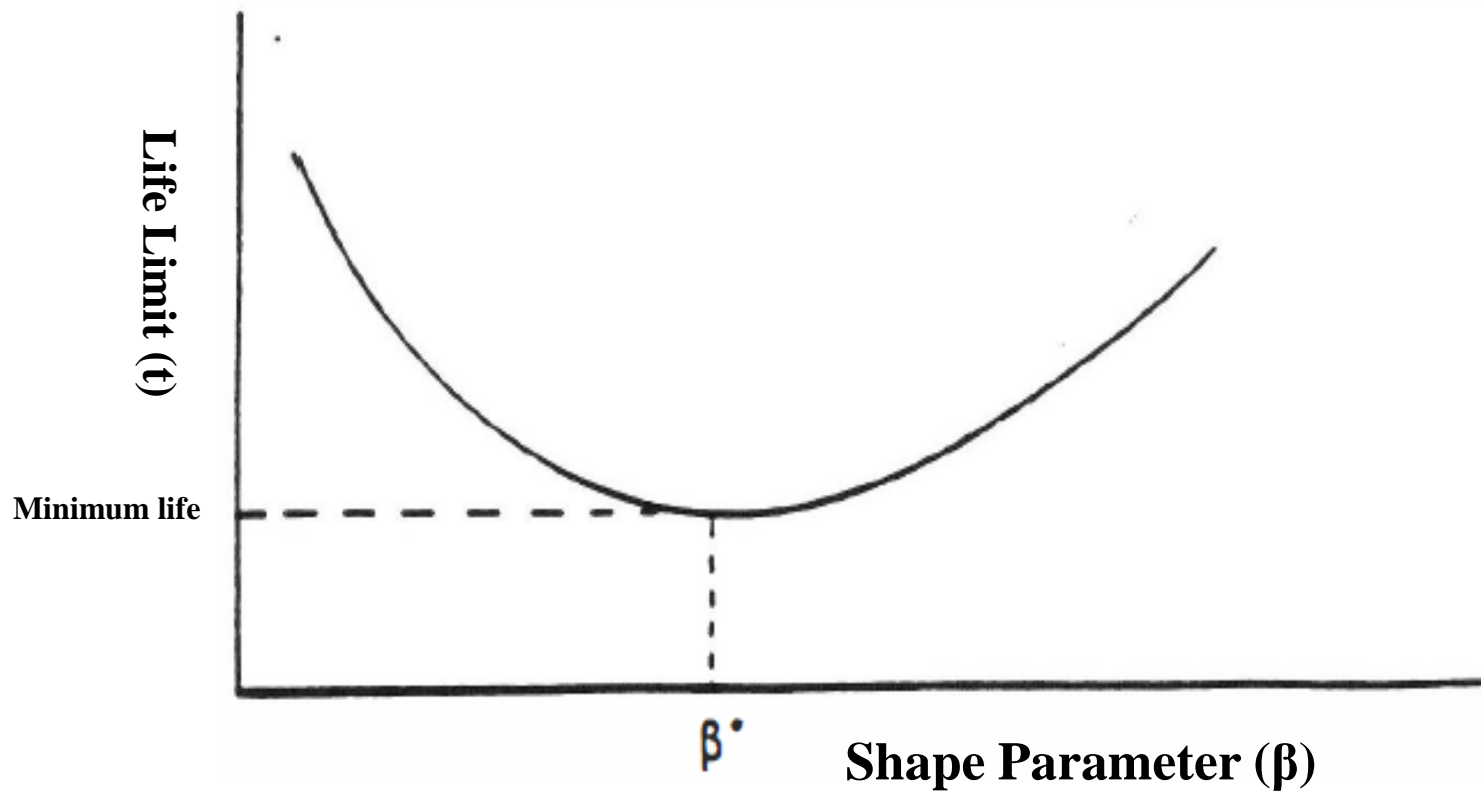
$$\eta \geq \left(\sum_{i=1}^n (t_i^\beta) / 2.3 \right)^{1/\beta}$$

- 3) Use the β and η in steps 1 and 2, and the specified single flight reliability (i.e., 0.995) to determine the value of t using:

$$P(T \geq t \mid T > t-m) = \text{Exp}[-(t/\eta)^\beta] / \text{Exp}[-((t-m)/\eta)^\beta]$$

- 4) Starting from the second iteration, check if the value of t obtained in step 3 is higher than the value of t obtained from the previous iteration. If so, go to step 6.
- 5) Increment the value of β and go to step 2.
- 6) The value of t is the minimum.

The Mathematical Bases – The Minimum Life



The Tool - The Process (Continued)

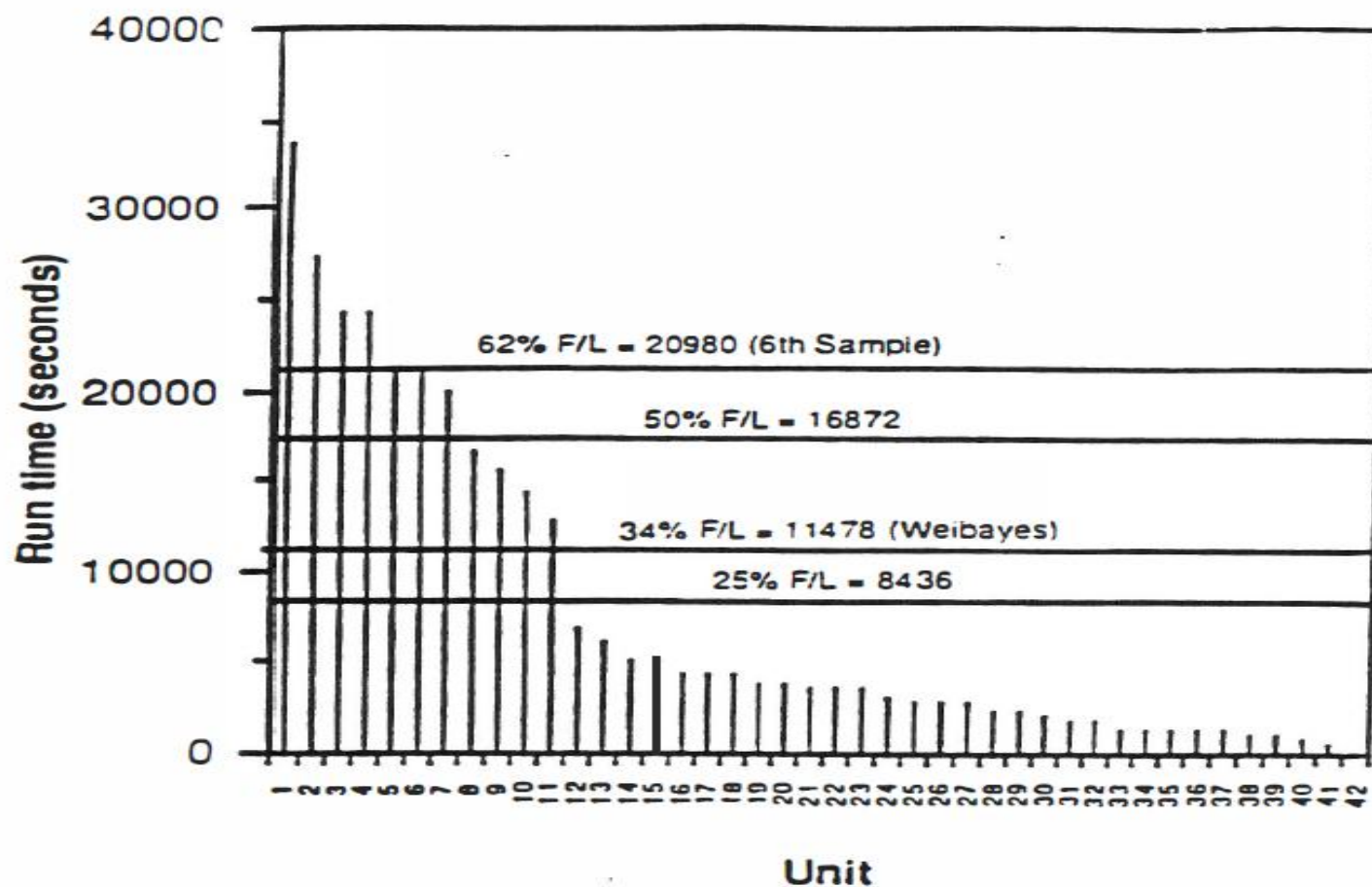
- The minimum life limit derived is then checked to make sure that it does not exceed 50% of the operating time of the fleet leading unit, or the minimum operating time of the six leading units.
- If the life limit derived is less than 25% of the fleet leading unit, the life limit is increased to 25%.
- The life limit derived has a lower bound of 25% of the fleet leading unit and an upper bound defined by the lesser of 50% of the fleet leading unit or the lowest of the six leading units.

The Application - The SSME Fuel Bleed Duct

- Data on 42 SME fuel bleed duct units with zero failures are used here to illustrate the application of the SFR tool.
- Using this data, for a 0.995 single flight reliability and 90% confidence level requirement, the minimum total time, t , derived is 11,478 seconds.
- This value of t represents approximately 34% of the operational experience of the fleet leading unit of 33,744 seconds.
- The 34% is higher than the lower bound of 25% (8,437 seconds) and lower than the upper bound of 50% (16,872 seconds) and the minimum of the six leading units (62% of the fleet leader) .
- Therefore, the life limit is 11,478 seconds.

The Application - The SSME Fuel Bleed Duct

The SSME Fuel Bleed Duct



Concluding Remarks

- **The statistical tool presented was implemented as part of the Space Shuttle Program requirement.**
- **The tool has been effectively used by the Shuttle Program since the early 1990's.**
- **This is a good example of how Statistical Engineering has helped the SSME program to reduce cost, increase availability, and maintain high level of reliability of critical hardware.**